Embedded
Code Generation

DEMO MODEL

Six-Phase PMSM

Controls for Dual-Star 6-Phase Permanent Magnet Synchronous Machine

Last updated in C2000 TSP 1.6.1

1 Overview

Multiphase machines are drawing more and more attention in Electric Vehicle (EV) industry. The potential advantages of multiphase machines, in comparison with three-phase machines, include: reduced torque pulsation, reduced harmonic content of the DC link current, improved stator magnetomotive force (MMF) waveform, improved efficiency, and reduced per phase current rating [1]. In addition, reliability is greatly improved since the machine can continue to operate even if one or (in some cases) several phases are lost.

The multiphase machine can be driven by separate inverters with independent energy sources. For example, the hybrid energy storage systems (HESS) using both batteries and ultracapacitors (UCs) is a popular solution recently [2].

This demo model shows the simulation of a 6-phase PMSM in dual-star connection, driven by two VSI (Voltage Source Inverter) using the cascaded speed and current control loops. It provides an explanation of the model-based control design workflow with the embedded code directly generated from the PLECS model using the PLECS TI C2000 Target Support Package. Combined with a PLECS RT Box, the performance of the MCU can be verified in real time.

1.1 Requirements

To run this demo model, the following items are needed (available at `www.plexim.com`):

- One PLECS RT Box with PLECS and PLECS Coder license
- One TI C2000 MCU LaunchPad with one RT Box LaunchPad Interface board
- The RT Box Target Support Package
- The TI C2000 Target Support Package
- (*Optional*) The initialization commands of the model feature a speed controller design using the Controls Toolbox from Matlab Simulink or Octave. If you use PLECS Blockset and have a Controls Toolbox available please uncomment the marked lines in the model initialization commands.

The Plant model runs on all versions of the RT Box. The Controller model supports direct flashing onto several MCU targets, as explained in Section 3.2. Ensure that for the TI 280049C LaunchPad, switches S6, S8, and S4 are set to 1 by pushing them to the dot side. Additionally, set switch S3.1 to 1 by pushing it to the BP (bypass) side.

Note This model contains model initialization commands that are accessible from:
PLECS Standalone: The menu **Simulation + Simulation Parameters... + Initializations**
PLECS Blockset: Right click in the **Simulink model window + Model Properties + Callbacks + InitFcn***

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2 Model

The top-level schematic contains two separate subsystems representing the controller and plant models. Both subsystems are enabled for code generation from the **Edit + Subsystem + Execution settings...** menu. This step is necessary to generate the model code for a subsystem via the PLECS Coder.

2.1 Plant

The power stage for the model is shown Fig. 1. It is composed of a 6-phase PMSM in dual-star configuration. The two sets of star-connected three-phase stator windings are shifted by 30 electrical degrees

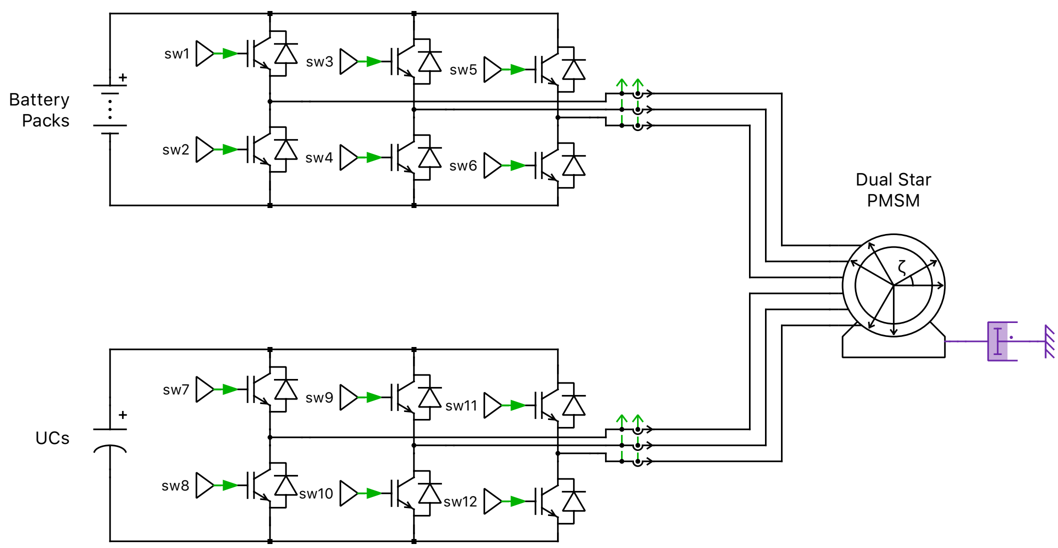

Figure 1: Power circuit of the 6-phase PMSM drive system

in space with isolated neutral points. Note that in this demo the 6-phase PMSM is a customized model instead of a library-linked component.

The two sets of machine windings are connected, through individual inverters, to independent energy sources, a battery and UCs. Both the battery and UCs supply the power during the start-up and acceleration process. Ultracapacitors are ideal when a quick charge is needed to fill a short-term power need; whereas batteries are chosen to provide long-term energy. Combining the two into a hybrid battery satisfies both needs and reduces battery stress, which reflects in a longer service life [3].

In this demo the UCs are utilized to provide large peak power, and the battery packs are responsible for a relatively fixed average power [4]. Both the battery packs and the UCs are modeled as DC voltage sources of 400 V, since in the hardware-in-the-loop (HIL) test using a DC voltage source is enough to calculate the DC power draw.

Dual-Star Permanent Magnet Synchronous Machine Model

The six-phase dual star electrical machine is modelled with two sets of dq rotor reference frames/coordinates [5]. For the first set $dq1$ the d-axis of the rotor is aligned with smallest airgap and the zero angle rotor position is when the d-axis is aligned with first phase. The second set $dq2$ is shifted by $\pi/6$.

The line-to-neutral voltages for each winding set are the inputs of the machine model and are transformed into the $dq12$ frame using two Park transformation blocks. The stator currents $i_{\mathrm{d1}}, i_{\mathrm{q1}}, i_{\mathrm{d2}}$ and i_{q2} are the state variables and outputs of the machine model model. This application does not feature a damper cage on the rotor which is typically used in high power applications. Fig. 2 shows the PMSM modeled in the conventional rotor reference frame (RRF).

The following is the state equation of the model:

$$\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} = \mathbf{L}^{-1}(-R_{\mathrm{s}}\mathbf{i} - \omega\mathbf{I}\mathbf{\Lambda} + \mathbf{v}_{\mathrm{s}})$$

where $\mathbf{i}$ is the stator and damper winding current vector, $\mathbf{L}$ is the inductance matrix, R_{s} the scalar stator and damper winding resistance, ω the electrical rotational speed, $\mathbf{I}$ a sparse coupling matrix of the stator phases, $\mathbf{\Lambda}$ the rotor flux vector and $\mathbf{v}_{\mathrm{s}}$ the stator voltages. In the equation above the current, voltage and flux vectors take the following form:

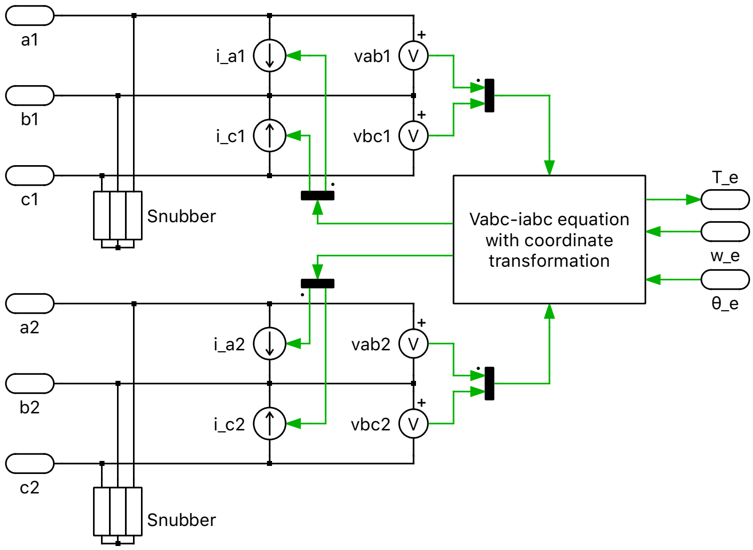

Figure 2: 6-Phase PMSM modeled in rotor reference frame

$$\mathbf{i} = \begin{pmatrix} i_{\mathrm{sd1}} \\ i_{\mathrm{sq1}} \\ i_{\mathrm{sd2}} \\ i_{\mathrm{sq2}} \end{pmatrix}, \quad \mathbf{v}_{\mathrm{s}} = \begin{pmatrix} v_{\mathrm{sd1}} \\ v_{\mathrm{sq1}} \\ v_{\mathrm{sd2}} \\ v_{\mathrm{sq2}} \end{pmatrix} \quad \text{and} \quad \mathbf{\Lambda}_{\mathrm{s}} = \begin{pmatrix} \Lambda_{\mathrm{sd1}} \\ \Lambda_{\mathrm{sq1}} \\ \Lambda_{\mathrm{sd2}} \\ \Lambda_{\mathrm{sq2}} \end{pmatrix}.$$

The inductance matrix has the form:

$$\mathbf{L} = \begin{pmatrix} L_{\mathrm{md}} + L_{\sigma} & 0 & L_{\mathrm{md}} & 0 \\ 0 & L_{\mathrm{mq}} + L_{\sigma} & 0 & L_{\mathrm{mq}} \\ L_{\mathrm{md}} & 0 & L_{\mathrm{md}} + L_{\sigma} & 0 \\ 0 & L_{\mathrm{mq}} & 0 & L_{\mathrm{mq}} + L_{\sigma} \end{pmatrix}.$$

The magnetization inductance L_{md} and L_{mq} is assumed to be equal in both sets of windings. The stator leakage inductance is represented by the term L_{σ}. The flux linkage is given by the following expression:

$$\mathbf{\Lambda}_{\mathrm{s}} = \mathbf{L}\mathbf{i} + \begin{pmatrix} \Psi \\ 0 \\ \Psi \\ 0 \end{pmatrix}.$$

The flux induced by the magnets affects only the d components of the flux linkage. The sparse matrix I couples the stator phases and only has the following non-zero elements: $I_{1,2} = -1$, $I_{2,1} = 1$, $I_{3,4} = -1$ and $I_{4,3} = 1$.

Note **Snubber Resistance:** The machine model relies on a current source implementation at the stator terminal, which connects to the two voltage source inverters (VSI). This is a problem for the open winding configuration of the machine because the state of the diodes inside the VSI can not be determined. To set a defined potential between the windings when either no VSI is connected or during the dead-time of the inverter half-bridges a snubber resistance needs to be added. This snubber resistance can make the system stiff if the resistance value is very high or when the leakage inductance of the machine is very small (the associated time constant is $\tau = L_\sigma / R_{\mathrm{snubber}}$). The snubber is chosen as $R = 10\,\mathrm{k}\Omega$ which still allows the model to be simulated with the non-stiff DOPRI solver in PLECS Standalone without sacrificing necessary simulation accuracy.

2.2 Controller

The "Controller" subsystem model is shown in Fig. 3. The cascaded speed and current control scheme follows the diagram presented in Fig. 8 of [4].

The "Speed Controller" subsystem contains first a speed PI regulator and afterwards a LPF (Low-Pass Filter) to divide the total current demand into that of inverter 1 and 2 individually. The generated inverter 1 and 2 q-axis current references (tag "I1q_Ref" and "I2q_Ref") enter respectively the subsystem "Current Controller 1" and "Current Controller 2".

The current control structure is derived according to the d-q frame equivalent circuits shown in Fig. 4. Several couplings exist between the equivalent circuits, which are represented by the back-EMF voltage sources and the mutual inductors. The current controller of the first winding is shown in Fig. 5, the feed-forward terms are added for decoupling purpose so that the plant looking from the output of the two PI controllers becomes a series connection of $L_\mathrm{d} = L_\mathrm{md} + L_\sigma$ ($L_\mathrm{q} = L_\mathrm{mq} + L_\sigma$) and R_s. The PI controllers can thus be parametrized independently between the d and q axis, using the maximum gain approach. The reference of the q-axis current is provided by the speed controller, while the d-axis current is set to zero. The output of the PI controllers are converted to duty cycles and fed to the PWM output blocks.

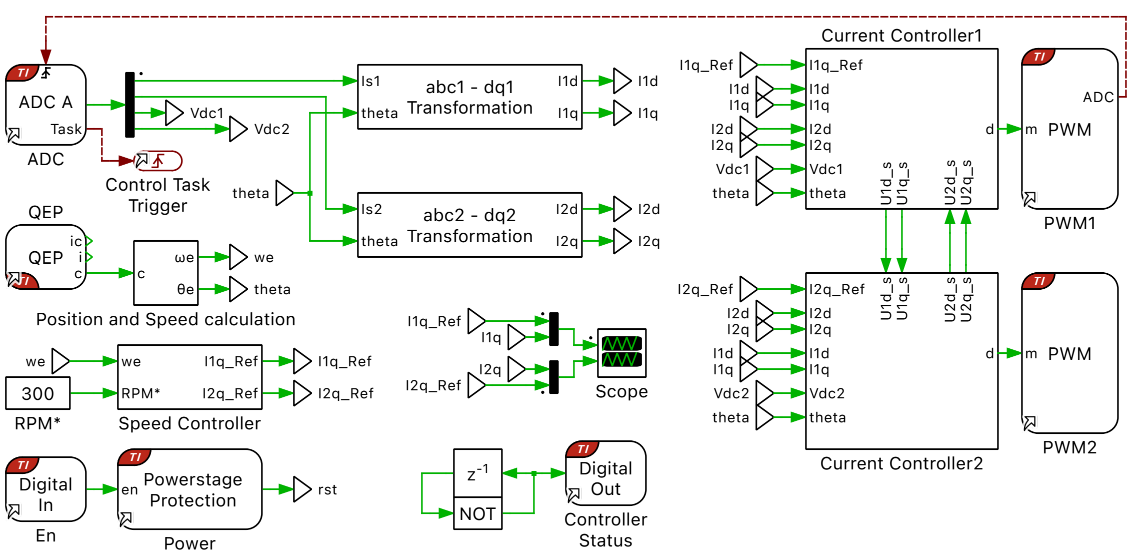

Figure 3: Controller circuit of the 6-phase PMSM drive system

Note that in order to make the Controller model applicable on different Microcontroller platforms using the same ADC-A unit of each, only two phase currents are measured instead of all three in each inverter assuming that the third phase current satisfies $i_\mathrm{c} = -(i_\mathrm{a} + i_\mathrm{b})$.

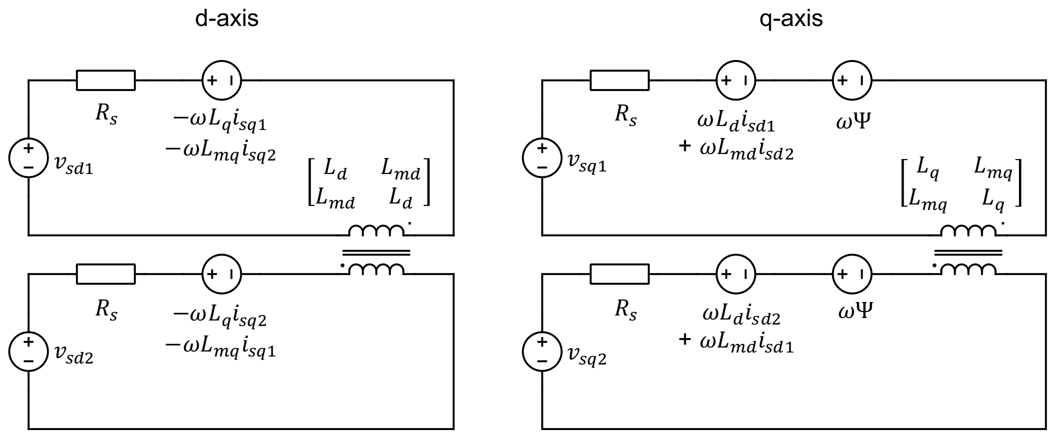

Figure 4: Equivalent circuit of the 6-phase PMSM in d-q frame for control design

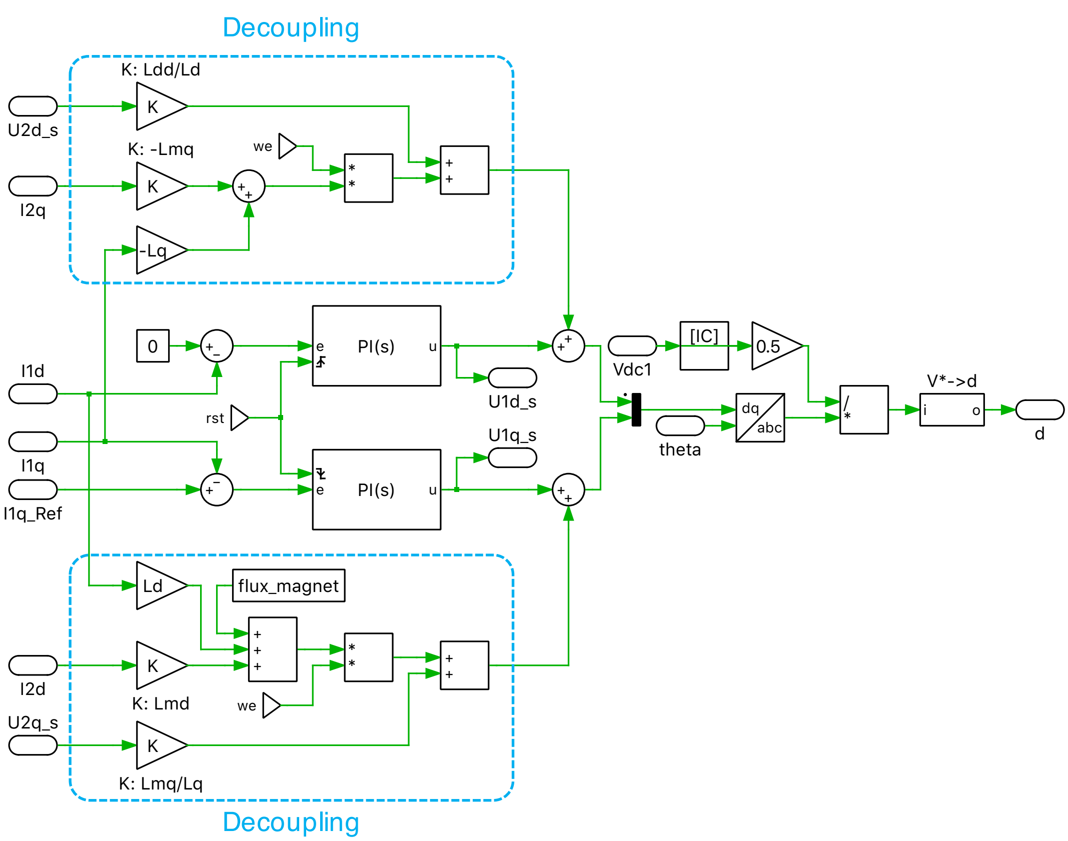

Figure 5: Current control structure of the first stator winding.

Frequency Dividing Coordinated Control

By the frequency dividing coordinated control strategy, the UCs respond to the high-frequency component in the load power fluctuation while the battery packs provide the low-frequency response. The frequency response of the LPF (Low-Pass Filter) employed in the frequency dividing unit is shown in Fig. 6 [4] .

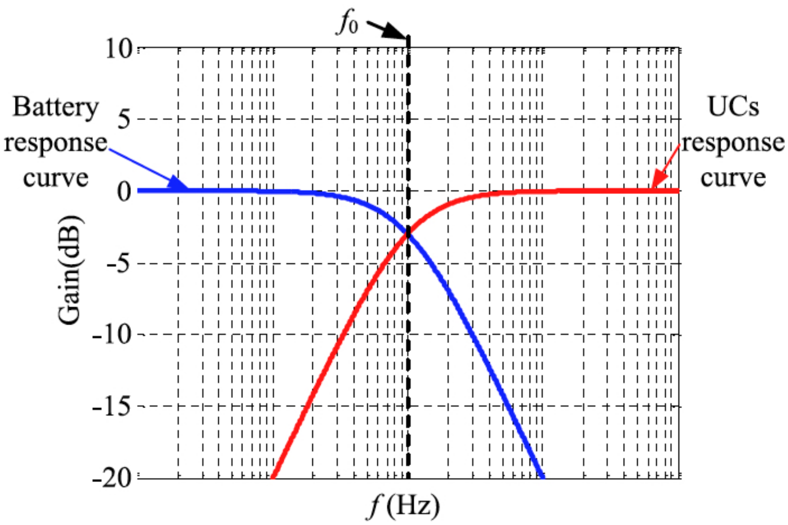

Figure 6: Frequency dividing coordinated control response by a LPF

3 Simulation

3.1 PLECS offline simulation result

The simulation model can be run offline on a desktop computer by choosing the **Simulation + Start** menu option. Fig. 7 shows the results from the PMSM in the "Plant" subsystem.

The machine starts up at 0 s with a speed reference of 300 RPM. The large transient torque is mainly provided by the inverter 2 currents supplied by the UCs. And the inverter 1 currents supplied by the battery packs are slowly ramping up due to the effect of the LPF explained in Fig. 6.

At 1.5 s, the machine speed is approaching steady state where inverter 2 is barely supplying any current and the main machine torque is provided by the battery packs via inverter 1. At this point, a speed reference jump from 300 RPM to 400 RPM is enabled. Similar dynamics happened till the machine speed reaches 400 RPM steady state again.

3.2 Configuring the TI C2000 Target

In addition to running a simulation of this demo model in offline mode on a computer, the "Controller" subsystem can be directly converted into target specific code for the TI C2000 MCUs. The default I/O configuration of all the peripheral blocks (ADC, PWM etc.) supports the TI 280039C [6], TI 280049C [7], TI 28069 [8], TI 28379D [10], TI 28P650DK9 [11] LaunchPads, and the TI 28388D [14] controlCARD.

Note Ensure that for the TI 280049C LaunchPad, switches S6, S8, and S4 are set to 1 by pushing them to the dot side. Additionally, set switch S3.1 to 1 by pushing it to the BP (bypass) side.

Additionally, the demo model allows for code generation for the TI 28377S [9] LaunchPad, as well as the TI 280039C [12] and TI 28379D [13] controlCARDs. To configure this, go to the **Model initialization commands** window from the **Simulation + Simulation Parameters... + Initializations** menu, and change the value of `board_type`, to select the desired board. You must also configure the corresponding **Target** and **Board** type in the **Coder Options** window accordingly. Furthermore, the model of the plant can be deployed on the PLECS RT Box for a hardware-in-the-loop (HIL) test of the generated code.

Follow the instructions below to upload the "Controller" subsystem to a TI MCU.

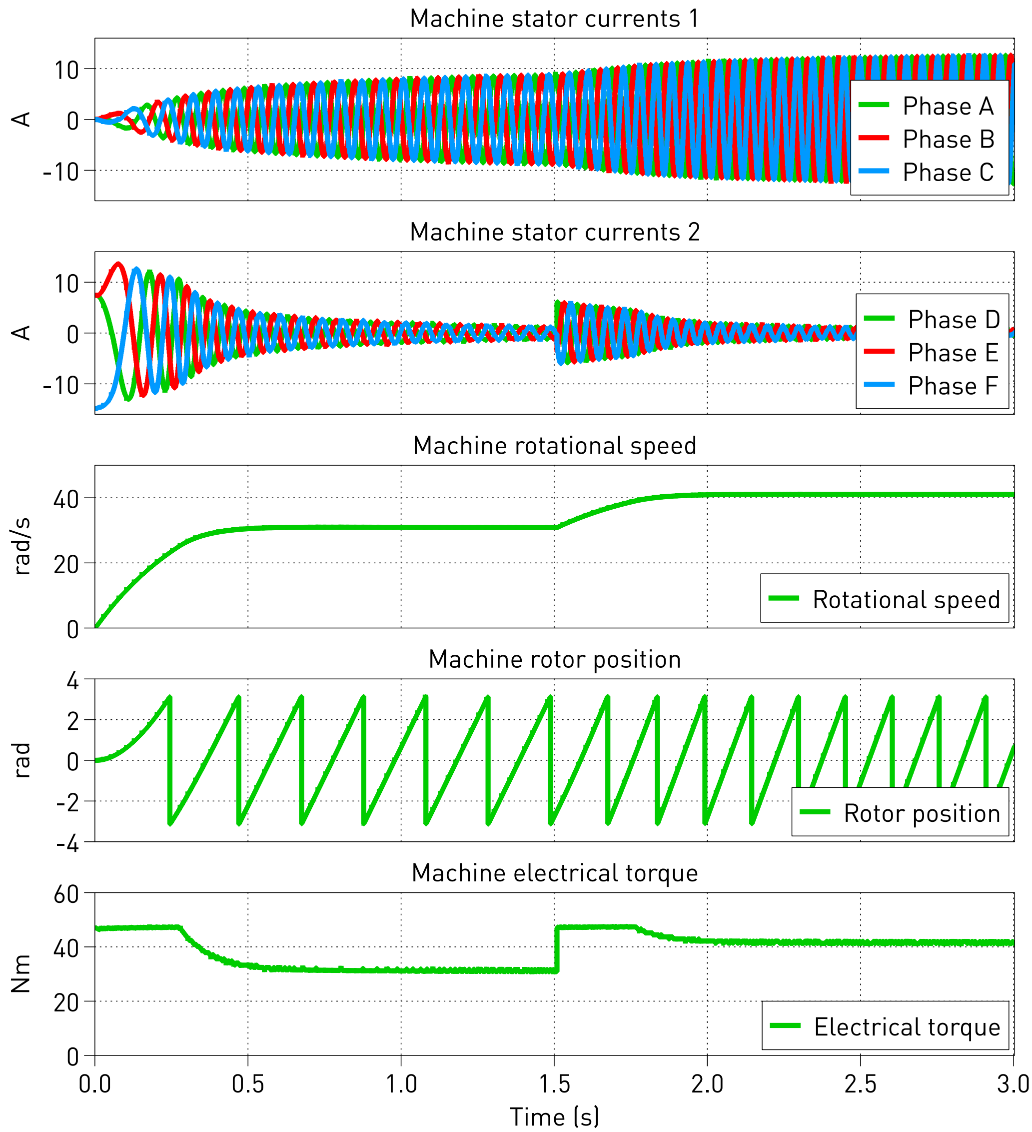

Figure 7: Offline simulation result of the 6-phase PMSM starting up with 300 RPM speed reference and change to 400 RPM at 1.5 s

- Connect the MCU to the host computer through a USB cable.
- From the **System** tab of the **Coder + Coder options...** window, select “Controller”.
- Next, from the **Target** tab, select the appropriate target from the dropdown menu. Then under the **General** sub-tab, select the desired **Build type**.
- Then, to `Build and program` the MCU directly from PLECS, choose either `Run from Flash` or `Run from RAM` as the **Build configuration** to program the MCU either to flash memory or to RAM respectively, then select `LaunchPad` as the **Board** type, and click **Build**.

If programmed correctly, the LED corresponding to GPIO “DO_DSP_LED” as listed in the model initialization commands should blink.

Note If using the RT Box LaunchPad Interface board, make sure that the **RST** jumper is open throughout the simulation.

3.3 Configuring the PLECS RT Box

Prior to controlling a real power stage with the programmed MCU, it is highly recommended to first verify the behavior of the controller using a PLECS RT Box and perform a HIL test. A typical hardware configuration is shown in Fig. 8, where the evaluation kit, a TI 28069M LaunchPad (the red board), is connected to the RT Box via an RT Box LaunchPad Interface (the green board).

Follow the instructions below to run a real-time model on the RT Box. Before building on the RT Box, ensure that you have already built the "Controller" subsystem on the appropriate TI MCU, as shown in Section 3.2.

- From the **System** tab of the **Coder + Coder options...** window, select “Plant”. Click the **Target** tab and select a target device. Then click **Build** to deploy the model to the target RT Box.
- Once the model is uploaded, from the **External Mode** tab of the **Coder options...** window, **Connect** to the RT Box and **Activate autotriggering** to observe the test results in real time.

If programmed correctly, the LED corresponding to “DO-31” of the RT Box LaunchPad Interface board should blink.

3.4 Executing a Closed-Loop HIL Test

Toggle the switch “DI-29” on the RT Box LaunchPad Interface board from low to high to enable the MCU. When the power stage is enabled, the LED corresponding to “DO-29” of the LaunchPad interface board should turn on. Observe the real-time waveforms in the Scope of the “Plant” subsystem.

Figure 8: Hardware setup of the HIL verification with the RT Box

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Note At this stage, verify that the LED corresponding to “DO-29” on the RT Box LaunchPad Interface board is turned on.

Toggling the switch “DI-29” on the RT Box LaunchPad Interface board from high to low should disable all the gating signals. “DO-29” of the LaunchPad Interface board should turn off. Toggling “DI-29” back to high will enable the PWM outputs once again.

In order to observe the control signals of the MCU, follow the instructions below to connect to the external mode of the TI MCU.

- First, **Disconnect** the “Plant” subsystem from the **External Mode** of the PLECS RT Box, if connected.
- Then, from the **System** menu on the left hand side of the **Coder + Coder options...** window, select “Controller”.

- Next, from the **External Mode** tab, select the appropriate **Target device** and click **Connect**.
- Then, **Activate autotriggering** to observe the test results in the “Controller” subsystem Scope.

Similarly, connect to the RT Box external mode following the instructions in Section 3.3.

The simulation results in Fig. 9 are the real-time results of the machine under the default 300 RPM speed reference. The figure shows the runtime waveforms when speed is stabilized at 300 RPM. They show good agreement with the offline simulation results in Fig. 7.

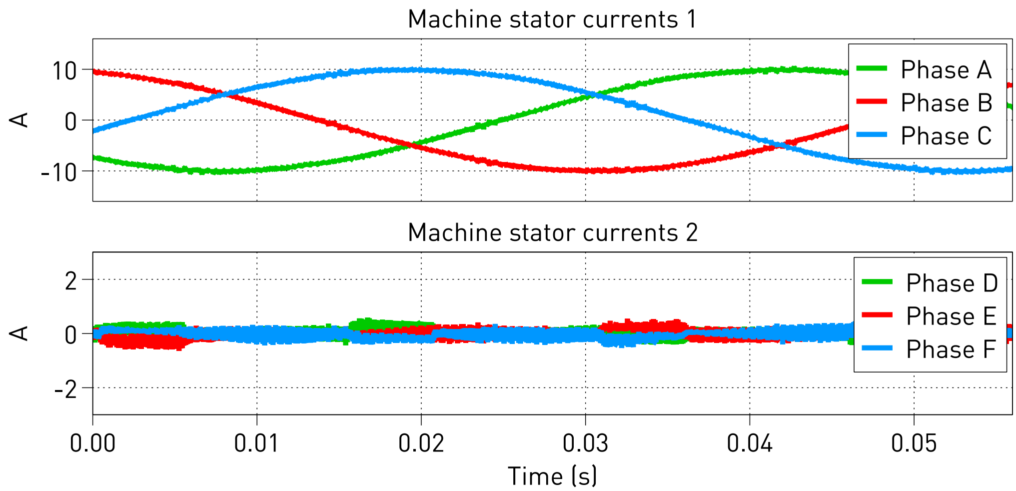

Figure 9: 6-phase PMSM waveforms running in real-time using the PLECS RT Box 1

The speed reference inside the “Controller” subsystem running on the MCU can be changed on the fly, since it has been added to the “Exceptions” list found in the **Parameter Inlining** tab of the **Coder options...** window, prior to building the model. A speed reference signal jump from 300 RPM up to 400 RPM can be performed in realtime, and the final waveforms in steady state also show good agreement with the offline simulation results in Fig. 7.

To conclude, the “Plant” model is discretized with fixed step-size $T_{\mathrm{disc.plant}}$ = 7 μs, and it is runnable on all RT Box platforms. The generated C-code is built onto the PLECS RT Box, and takes an average of 80% execution time. The “Controller” model runs on the MCU with time step equal to switching period, which means $T_{\mathrm{disc.ctrl}} = T_{\mathrm{sw}} = 1/10\,\mathrm{kHz} = 100\,\mu\mathrm{s}$.

4 Conclusion

This model demonstrates a 6-phase PMSM drive with hybrid energy storage system that is an emerging topic in the EV industry. The control system supports embedded code generation for TI C2000 MCUs. It can run in both offline mode, as well as in real-time. The controller consists of an outer speed loop and an inner current loop. The current loop features a frequency dividing coordinated control to distribute the current reference to each inverter, followed by PI compensator for each inverter d-q axis current.

References

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[14] TI C2000 F28388D controlCARD evaluation module,
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Revision History:

C2000 TSP 1.3.1	First release
C2000 TSP 1.4.5	Updated the speed calculation block, and the web links
C2000 TSP 1.5.1	Added support for 28388D and 28379D controlCARD targets
C2000 TSP 1.6.1	Added support for 280039C LaunchPad and controlCARD targets, and auto-pin selection

How to Contact Plexim:

☎ +41 44 533 51 00 Phone

+41 44 533 51 01 Fax

✉ Plexim GmbH Mail
Technoparkstrasse 1
8005 Zurich
Switzerland

@ `info@plexim.com` Email

`http://www.plexim.com` Web

Embedded Code Generation Demo Model